

## Circulation in Shelikof Strait, Alaska\*

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### ABSTRACT

Extensive hydrographic surveys were conducted in Shelikof Strait in March and October 1985. The data are used to describe circulation and property distributions and the changes that occurred. The upper layer flows to the southwest throughout the year, but greatest speeds occur in the fall when surface waters are least saline because of a maximum in freshwater discharge. The deep water has its source to the south, and the properties seem to result from vertical mixing of this southern water. Thus Shelikof Strait has an estuarine-like circulation with a northward, deep inflow.

Property distributions showed that isolines were usually deepest on the right side of the channel looking to the southwest; greatest baroclinic speeds were often there also. Differential Ekman pumping may contribute to the development of this structure and its changes. Volume transport estimates varied considerably. In October the southwest flow bifurcated, with part continuing along the Alaska Peninsula and the rest exiting the main channel to the south; in March all upper-layer flow followed the main channel. Shelikof Strait appears to be a system influenced by both density-driven and wind-driven effects.

### 1. Introduction

Shelikof Strait and its associated sea valley extend ~450 km between the Alaska Peninsula and the Kodiak Island plateau in the northwestern Gulf of Alaska. We use the term "Shelikof Strait" for the entire deep feature bounded by the 100-fathom (183-m) isobaths (typical width ~40 km) as well as shoaler areas just west of the Kenai Peninsula (Fig. 1). Maximum depths (~300 m) occur in the portion of the strait between ~56.5° and ~57.8°N; where the sea valley crosses the shelf break west of Chirikof Island, sill depth is ~200 m. The major circulation features in the region (Fig. 1) are the offshore Alaskan Stream and the Alaska Coastal Current (ACC; Royer, 1981), which flows to the southwest through Shelikof Strait.

In March and October 1985 comprehensive hydrographic surveys were conducted in the Shelikof Strait region (Fig. 2). Limited data also were obtained at other times, and they are used to a minor extent below. This work is part of a new NOAA program, the Fishery Oceanography Coordinated Investigations (FOCI). In 1985 FOCI efforts were concentrated in Shelikof Strait, where large concentrations of spawning pollock (*Theragra chalcogramma*) occur during spring. The work described in this paper is directed at understanding major circulation features that may affect the planktonic eggs and larvae of pollock. In particular, we are

concerned with the continuity of flow along the Alaska peninsula and the intensity of seaward flow down the sea valley. Although various biological and chemical data were obtained during 1985, this study deals primarily with the physical environment during the contrasting conditions of winter and fall 1985. Reed et al. (1986) give a more complete presentation of the data.

### 2. Data and methods

The CTD (conductivity/temperature/depth) casts made during March and October are shown in Fig. 2. The same numbered grid was used, but every station was not occupied on each cruise. Stations with the same number, however, were at essentially the same site. CTD casts were made with Grundy or Seabird systems, which sampled 5 or 24 times per second, respectively, for values of temperature, conductivity, and pressure. Data were recorded only during the downcast at a lowering rate of ~30 m min<sup>-1</sup>. Bottle samples were taken at most stations to provide calibration. Data from continuously increasing depth were "despiked" to remove extreme values, and then they were averaged over 1-m intervals to obtain temperature and salinity from which density and geopotential anomaly were computed.

Nutrient samples were collected using Niskin bottles deployed on the CTD-rosette sampler, and the samples were frozen until analysis could be made after each cruise. Standard nutrients were measured on a Technicon Autoanalyzer II. Selected nitrate data are presented here.

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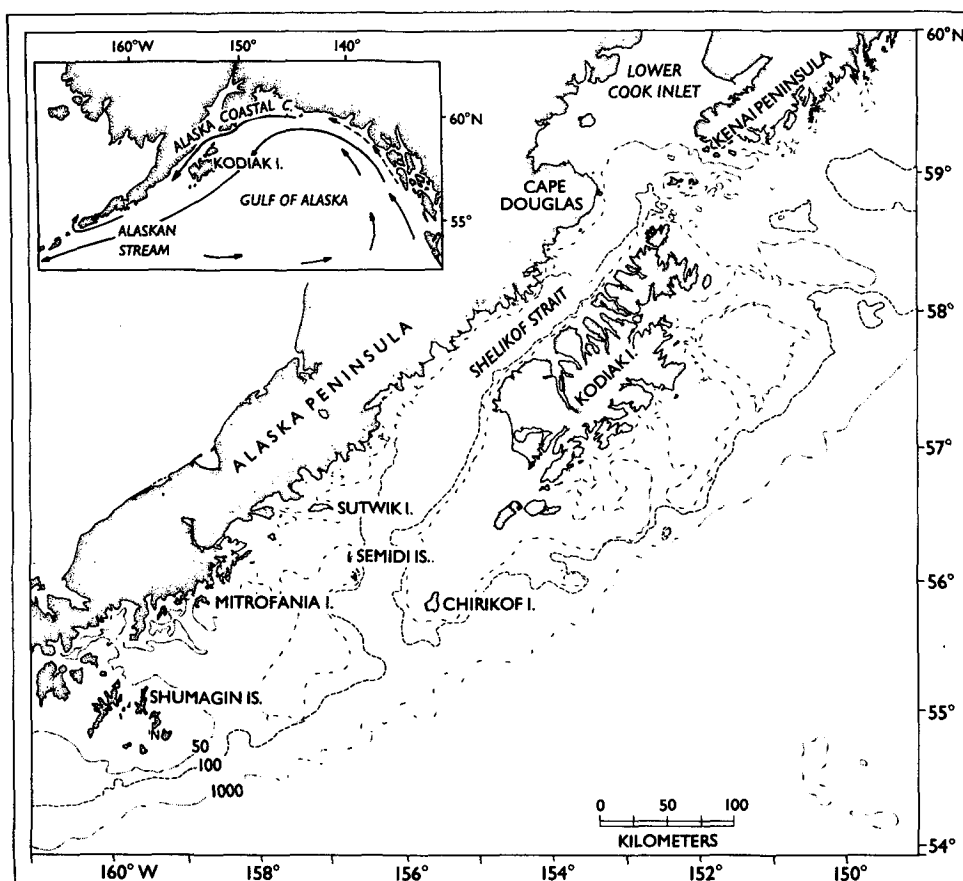


FIG. 1. Location of the study area with place names and bathymetry (in fathoms; 1 fathom = 1.83 m). The insert indicates the typical upper-ocean circulation.

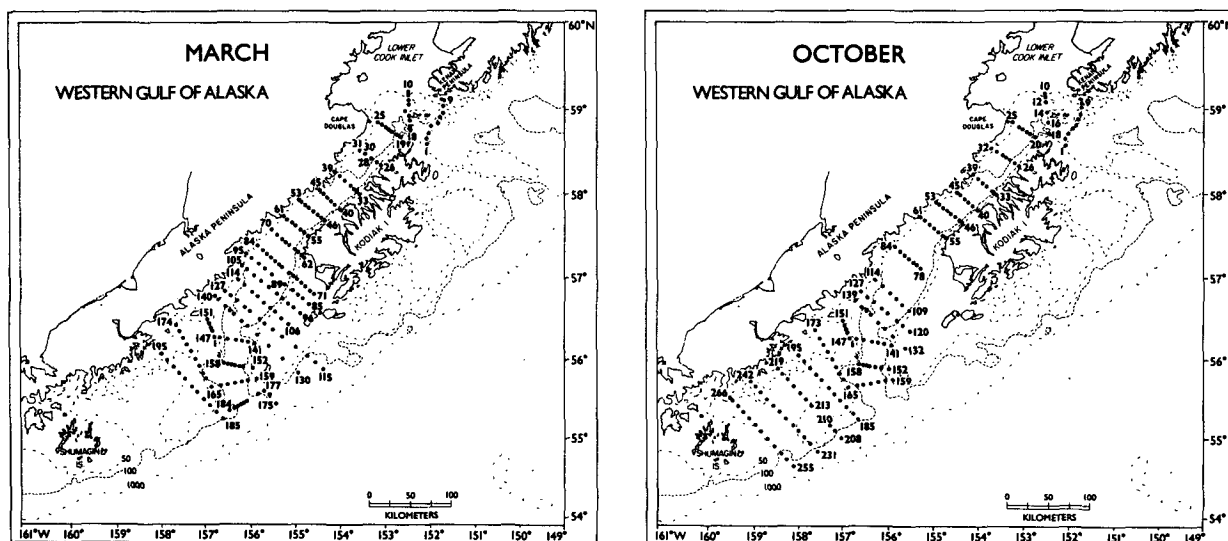


FIG. 2. Location of CTD stations during 12–28 March 1985 and 9–25 October 1985.

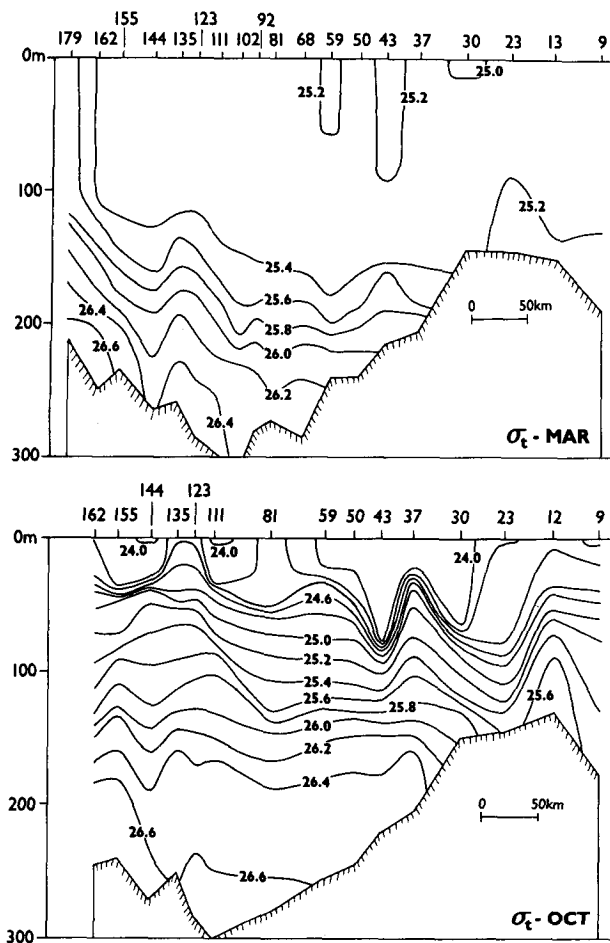


FIG. 3. Vertical sections of sigma- $t$  density along the main channel in Shelikof Strait during March and October 1985.

### 3. Estuarine-type circulation

The upper-ocean circulation in Shelikof Strait consists of the ACC, which enters the passage just off the Kenai Peninsula (Fig. 1; Schumacher and Reed, 1980). What is the source of the deep and bottom waters, however? Is it the deeper portion of the entering ACC water, or is it northward intrusions of slope water from the southern end of the strait as suggested by Schumacher et al. (1978)? That is, does the system have a circulation pattern similar to an estuary?

Figure 3 shows vertical sections of sigma- $t$  density during March and October 1985 from the southern end of the strait (left side) to the northern end (right side) using stations approximately in midchannel. It is apparent that the entering ACC water (station 9, or other stations on this line) was not dense enough to be the source of water below  $\sim 150$  m, which appears to have entered from the south. Furthermore, in March the isopycnal slopes below 150 m indicate a large pressure gradient (cf. Bretschneider et al., 1985, for similar

results in an estuarine system). The deep slopes in October were less extreme, which suggests that the intensity of the inflow may vary. Another strong argument for an estuarine-like system is the distribution of nitrate (Fig. 4); the entering ACC water did not have concentrations  $> 15 \mu\text{-at l}^{-1}$ , but the deep values were  $\sim 30 \mu\text{-at l}^{-1}$  and must have had their source in the deep waters to the south.

Figure 5 (where data for July 1985 are also included) presents temperature-salinity plots at station 153 (near the southern entrance to the Strait) and at station 61 (off the Alaska Peninsula near  $58^\circ\text{N}$ ). The July and October plots suggest that the bottom water at station 61 could have been formed by mixing of the temperature minimum, temperature maximum, and bottom waters at station 153. In March, however, the bottom water at station 61 was too warm to result from this three-point mixing unless the bottom water at station 153 was cooler than previously and the properties at station 61 resulted from mixing of previous water types. Results from thermistors on current meters near the bottom along the section between stations 152 and 158 indicate that the February temperature was  $\sim 5.8^\circ\text{C}$

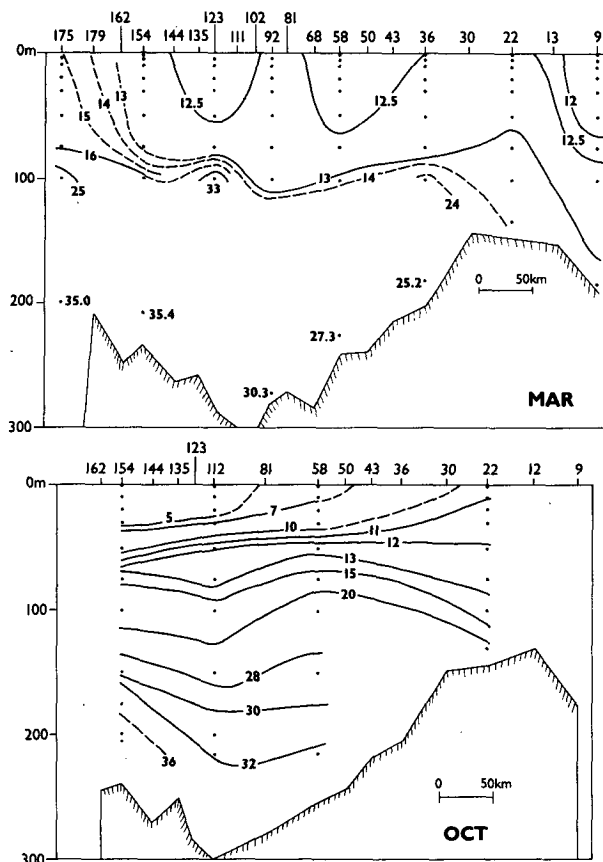


FIG. 4. Vertical sections of nitrate ( $\mu\text{-at l}^{-1}$ ) along the main channel in Shelikof Strait during March and October 1985.

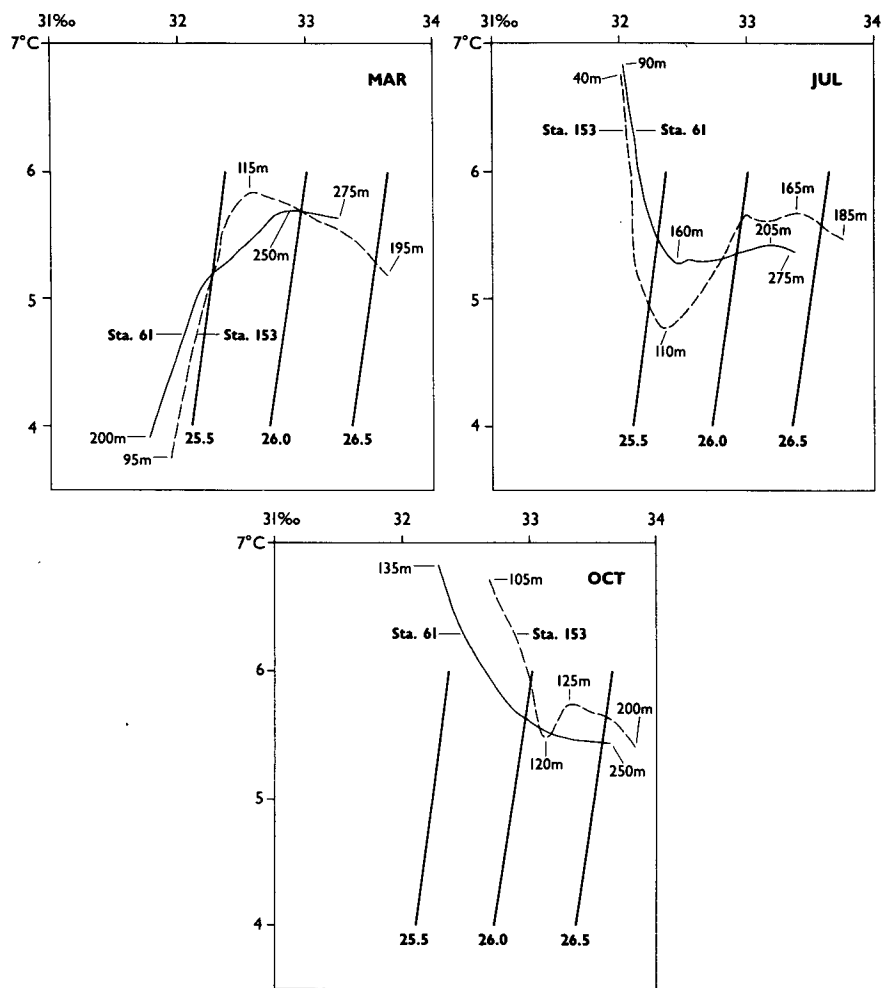
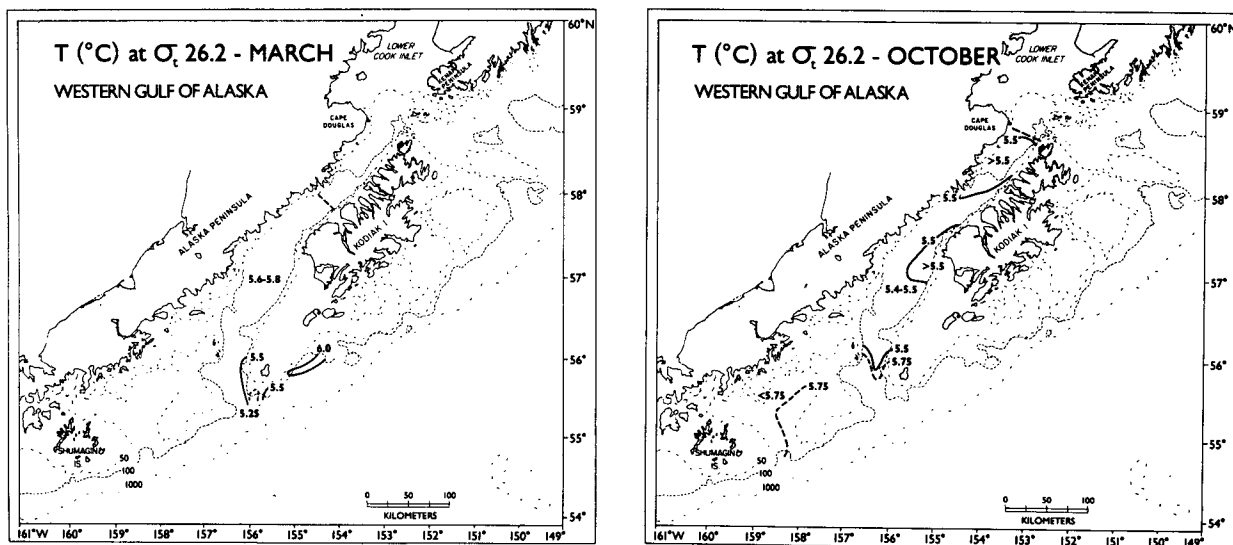


FIG. 5. Temperature-salinity diagrams at stations 153 and 61 for March, July and October 1985.

FIG. 6. Temperature (°C) at the sigma- $t$  density of 26.2 during March and October 1985. Dashed lines indicate the northern limit of data coverage.

with rapid cooling in March, which supports this suggestion.

Figure 6 presents temperature on the sigma- $t$  surface of 26.2 (typically 150–250 m depths). In both months the largest lateral gradients were at the southern end of the strait, and temperatures to the north varied little more than 0.1°C. This pattern suggests that deep waters attain their properties rather abruptly and not through uniform lateral mixing. Figure 6, and the fact that bottom waters to the north seem to have components of southern temperature minimum and maximum waters (Fig. 5), support the existence of vertical mixing, perhaps as a result of the influence of tidal currents on the inflowing deep water.

#### 4. Geostrophic flow

Since the data support an estuarine-type circulation for Shelikof Strait, an intermediate reference level should be used for computations of geostrophic flow. The strait is wide enough to expect Coriolis effects to be important ( $\sim 40$  km versus 10–15 km for the internal radius of deformation), but we do not know how well the geostrophic relation reflects actual circulation. The barotropic component of flow may attain appreciable speeds, especially in winter (Schumacher and Reed, 1980, 1986). With these caveats in mind, we will present geostrophic flow and volume transport estimates referred to an intermediate reference level, which yields much more plausible results than computations referred to the bottom. This does not imply that a single "level of no motion," invariant over space and time, actually exists. We have chosen 150 db, however, and it is used throughout. Some support for this choice may be inferred from the along-channel sigma- $t$  and nitrate distributions (Figs. 3 and 4). Also, the entering

ACC water (off the Kenai Peninsula) flows through a channel with a sill depth of  $\sim 150$  m, which may affect the lower boundary of the outflow downstream. Finally, current measurements were made from August 1984 to July 1985 on the section between stations 152 and 158. Current meters on the three moorings at depths of 185, 205 and 165 m all showed weak northward flow, while weak southward flow occurred above at depths of 105, 120 and 120 m.

Figure 7 presents the geopotential topography at the sea surface referred to 150 db for March and October. In March the ACC entered the strait off the Kenai Peninsula and flowed southwest. The flow was relatively weak, except for a region of fairly intense flow near the southern end of the strait. October had a much more intense baroclinic circulation than March. This is a typical seasonal feature resulting from the fall maximum in freshwater discharge (Schumacher and Reed, 1980; Royer, 1981). ACC waters entered the northern passage off the Kenai Peninsula, but the flow had intensified appreciably near Kodiak Island. The isolines suggest considerable meandering as discussed by Mysak et al. (1981), and the flow appears to have split and rejoined in places. At the southern end of the strait, there was a system of counterflows. Unlike conditions in March, a significant portion of the flow continued westward along the Alaska Peninsula, and this branch appeared to intensify near the western limit of the data.

It should be stressed again that we are only dealing with the baroclinic, geostrophic component of flow and that barotropic or other flows (near-surface wind drift, vortex stretching effects, wave motion, etc.) may also be important. A reviewer suggested that net flows might be generated by rectification of tidal currents. Currents were measured at six sites (on lines 55–61 and 152–158) in the main channel during 1984–85. The dom-

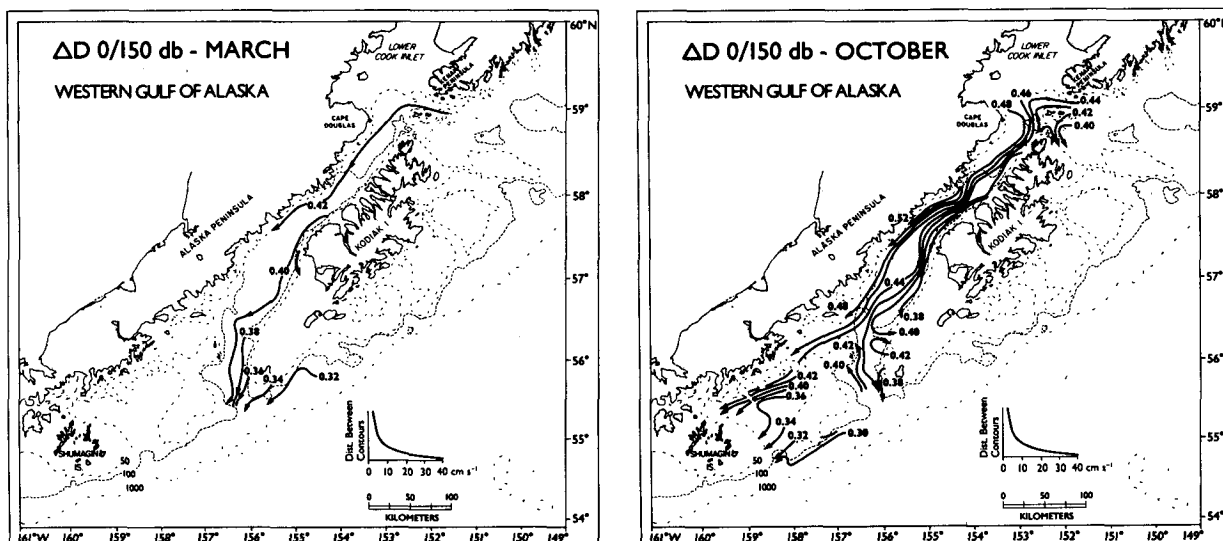


FIG. 7. Geopotential topography ( $\Delta D$ , dyn m) of the sea surface referred to 150 db, March and October 1985.

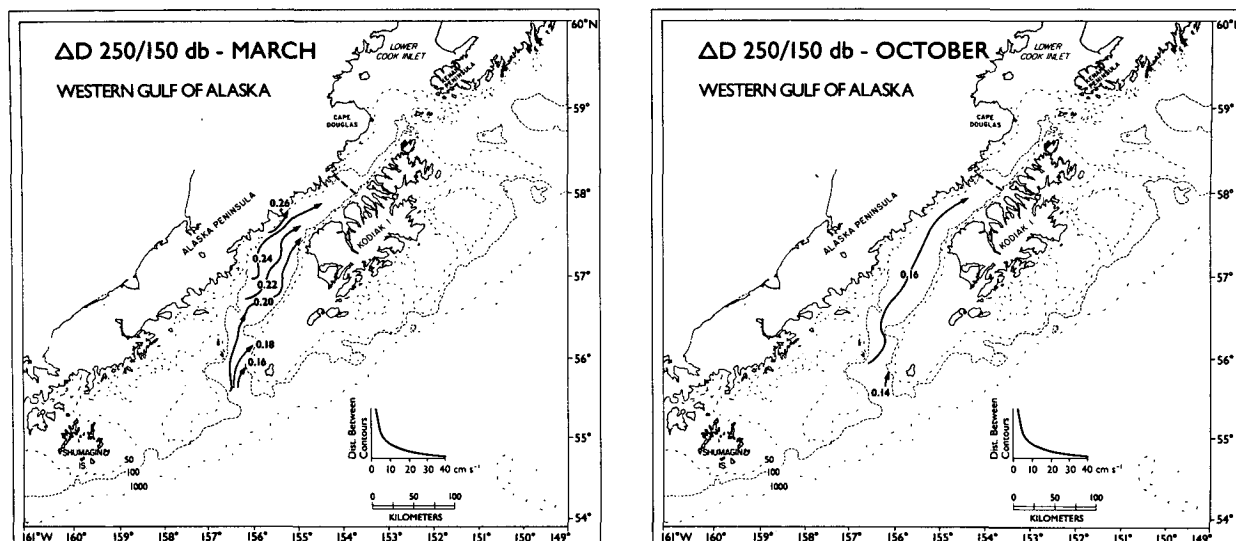


FIG. 8. Geopotential topography ( $\Delta D$ , dyn m) of the 250-db surface, referred to 150 db, March and October 1985. Dashed lines indicate the northern limit of data coverage.

inant  $M_2$  amplitudes within 15 m of the bottom varied from 13 to 26  $\text{cm s}^{-1}$ , and they were essentially reversing flows aligned along the channel. Hence tidal rectification is unlikely to be significant.

Figure 8 shows geopotential topography at 250 db referred to 150 db. Such a presentation is quite sensitive to the reference level chosen, and an actual level surface may vary in space and time. The results appear reasonable, however, and are in agreement with other evidence that Shelikof Strait has an estuarine-like circulation. In March there was a fairly intense northward inflow throughout the region where depths exceed 250 m. In October, however, the inflow appeared to be considerably weaker than in winter. Figure 9 shows vertical sections off the southern end of Kodiak Island (see Fig. 2) in March and October. The March data show the mixed layer extending almost to 200 m on the left side of the section, and there were strong slopes in the deep water. In October the mixed layer depth was less than 50 m, and deep density slopes were moderate. Thus the depth of the mixed layer seems to have important effects on the cross-channel distribution of density and the intensity of inflow (cf. Knauss, 1978).

## 5. Volume transport

Volume transport computations are even more sensitive to choice of a reference level than presentations of geopotential topography. Initial computations for each line or section gave five- to ten-fold variations in the main channel of the strait. As discussed below, it is believed that some of this variability is real, but some of it may result from changes in the level surface, some lines not spanning the entire strait, and lack of syn-

opticity in the data. Consequently, we decided to reduce the variability somewhat by averaging the results over the following regions: 1) the upper strait where water depths are only  $\sim 150$  m, 2) between Kodiak Island and the Alaska Peninsula where large orographic features are present, 3) downstream from Kodiak Island to where the upper flow sometimes bifurcates in the vicinity of the Semidi Islands, 4) the southern end of the main channel, and 5) two regions to the west along the Alaska Peninsula. The results appear plausible, and the original variability is indicated by the standard deviations given.

Table 1 presents the baroclinic volume transports, computed over 10-db intervals, for March. The 0 to 150-db transport increased in the vicinity of Kodiak Island, and the greatest variability also occurred there. There was a further increase at the southern end of the strait in agreement with Fig. 7. Transport west of the main channel was insignificant. Water depths do not generally exceed 150 m for the northernmost group of stations, but to the south, transports below 150 db were fairly large and constant. Except for an increase at the southernmost group, the total transport was also relatively constant. This suggests that the increase in upper-layer transport occurred to compensate for the deep inflow. In fact, the correlation coefficient between upper and deep transports (computed from the unaveraged data) is 0.77, which is significant at the 99% level. Such a relation was not present in October, however.

Table 2 presents the October transports. The upper-layer transport, and the variability, was considerably larger than in March. Again, there was a large increase in transport near Kodiak Island. This was not a result of deep inflows, which were quite small. The large de-

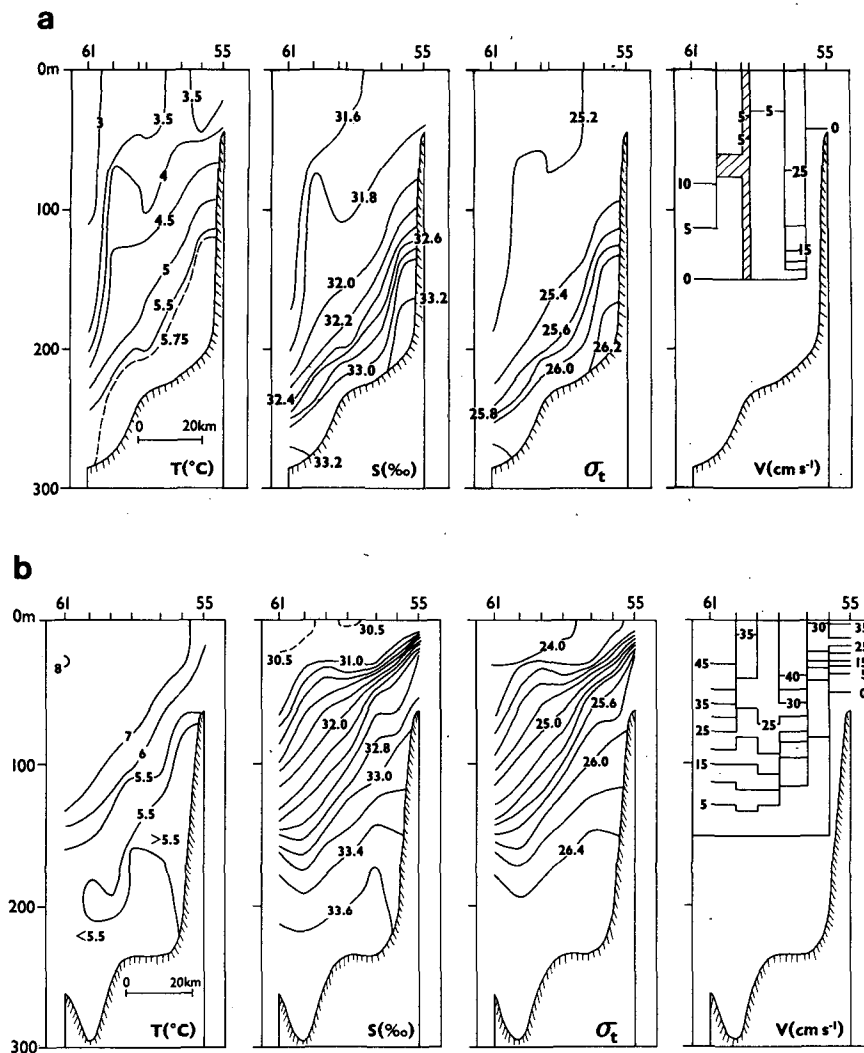


FIG. 9. Vertical sections of temperature ( $^{\circ}\text{C}$ ), salinity ( $\text{‰}$ ), sigma- $t$  density, and geostrophic flow ( $\text{cm s}^{-1}$ ) for stations 55–61, (a) 16 March 1985 and (b) 21 October 1985. Unhatched regions on the geostrophic flow sections indicate flow to the southwest; hatched regions indicate flow to the northeast.

crease at the southernmost group was not balanced by the flow ( $0.13 \times 10^6 \text{ m}^3 \text{ s}^{-1}$ ) that was diverted westward. Along the Alaska Peninsula west of  $\sim 158^{\circ}\text{W}$ , there was a further increase in transport. This could be produced by northward inflow into the region east of the Shumagin Islands. A computation of transport across the line bounded by stations 185 and 255 (see Fig. 2 and Table 2) gives a northward flow of  $0.47 \times 10^6 \text{ m}^3 \text{ s}^{-1}$ , which almost exactly balances the increase found.

A feature common to both March and October was an abrupt increase in upper-layer transport in the vicinity of Kodiak Island. This may have occurred in March to compensate for the large, deep inflow, but this is not a plausible mechanism in October. This is a fairly constricted area with large orographic features

on both the Alaska Peninsula and Kodiak Island, and these features have effects on the wind field in their vicinity (Macklin et al., 1984). A possible mechanism for producing changes in transport is differential Ekman pumping. We do not have continuous wind data over large parts of the system, but shipboard observations indicated winds were frequently from the northeast. Furthermore, a research aircraft flight on 28 March 1985 measured winds on two sections across the strait; average midchannel winds were  $10 \text{ m s}^{-1}$  from the northeast with average values of  $6 \text{ m s}^{-1}$  near the Alaska Peninsula and  $8 \text{ m s}^{-1}$  near Kodiak Island (A. Macklin, personal communication). With these gradients between midchannel and both coasts, a computation indicates isopycnal slopes could be increased

TABLE 1. Mean volume transport and standard deviation for groups of CTD sections (see text) for the upper 150 db and from 150 db to the bottom (using 150 db as the reference level), March 1985. The groups are arranged from north to south in the main channel of Shelikof Strait, with results along the Alaska Peninsula listed last; positive values indicate westward or southward transport, and negative values indicate eastward or northward transport.

Stations	Dates (March 1985)	Volume transport ( $10^6 \text{ m}^3 \text{ s}^{-1}$ )					
		0 to 150 db		150 db to bottom		Total	
		Mean	Std. dev.	Mean	Std. dev.	Mean	Std. dev.
1-9, 10-18, 19-25, 26-31, 33-39	12-15	0.14	0.05	0.00	0.00	0.14	0.05
40-45, 46-53, 55-61, 62-70, 75-84	15-19	0.28	0.16	-0.15	0.09	0.13	0.09
88-95, 98-105, 108-114, 121-127, 132-140	19-23	0.23	0.04	-0.13	0.03	0.10	0.03
141-146, 152-158, 159-164, 177-184	24-26	0.35	0.09	-0.13	0.09	0.22	0.03
147-151, 169-174, 185-195	26-27	0.02	0.01	—	—	0.02	0.01

by 40 m in a week, which would increase volume transport. How such a spinup would be translated downstream is hard to envision.

## 6. Mechanisms

Thus far we have described Shelikof Strait as an estuarine-like system, albeit one in which Coriolis effects are important. We now attempt to delve further into the mechanisms of importance to the region. It should be emphasized that the strait has one important difference from "pure" estuaries (such as tidal rivers flowing to sea): it is open at both ends and has a coastal current flowing through it. Hence the controls placed upon the circulation by physical boundaries are less strict than in tidal rivers.

There does appear to be sufficient fresh water available to drive an estuarine-like circulation, however. Results from a hydrologic model (Royer, 1982) show that coastal discharge enters the Gulf of Alaska as a line source; long-term mean discharge varies seasonally from about  $0.01 \times 10^6 \text{ m}^3 \text{ s}^{-1}$  in March to  $0.04 \times 10^6 \text{ m}^3 \text{ s}^{-1}$  in October, and the mean annual discharge is slightly greater than that of the Mississippi River. In

estuaries the upper-layer outflow is typically 10–20 times the fresh water inflow. Hence the discharges above should lead to outflows that are at least comparable to those computed (Tables 1 and 2).

It is uncertain, however, if flow in the strait is largely density-driven or wind-driven. Stommel and Leetma (1972) developed a model for a broad estuarine system which allows one to assess the relative importance of these effects. Using observed salinity data on various sections, their salinity length scales were computed for March and October. The results were generally close to  $1.0 \times 10^8 \text{ cm}$ , which contrasts with a value of  $\sim 0.4 \times 10^8 \text{ cm}$  for pure density-driven flows at modest Ekman numbers. It thus appears that Shelikof Strait is neither wholly density-driven nor wind-driven and is intermediate in character.

Wind effects on the system may take various forms. Upper-layer wind drift or Ekman transport would be appreciable under strong winds. As noted before, there is considerable evidence in current records for significant barotropic flows on various time scales. Finally, Ekman pumping, resulting from spatially nonuniform winds, seems likely to be important in altering the baroclinic flow.

TABLE 2. As in Table 1 except for October 1985.

Stations	Dates (October 1985)	Volume transport ( $10^6 \text{ m}^3 \text{ s}^{-1}$ )					
		0 to 150 db		150 db to bottom		Total	
		Mean	Std. dev.	Mean	Std. dev.	Mean	Std. dev.
1-9, 10-18, 20-25, 26-32, 33-39	22-25	0.27	0.35	-0.01	0.01	0.27	0.35
40-45, 46-53, 55-61, 78-84	21-22	0.70	0.43	-0.05	0.02	0.66	0.45
109-114, 120-127	17-18	0.66	0.13	-0.04	0.03	0.62	0.10
132-139, 141-146, 152-158, 158-164	9-17	0.22	0.17	-0.02	0.01	0.20	0.17
147-151, 169-173, 185-195	11-12	0.13	0.04	—	—	0.13	0.04
213-219, 235-242, 255-266	14-16	0.61	0.15	0.00	—	0.61	0.15
185-255	12-15	0.47	—	-0.01	—	0.46	—

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